Crashdynamics with DYNA3D: Capabilities and Research Directions

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CRASHDYNAMICS WITH DYNA3D: CAPABILITIES AND RESEARCH DIRECTIONS

This paper discusses the application of the explicit nonlinear finite element analysis code DYNA3D to crashworthiness problems. Emphasized in the first part of this work are the most important capabilities of an explicit code for crashworthiness analyses. The remainder of the paper discusses the areas with significant research promise for the computational simulation of crash events.

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WHAT IS CRASHWORTHINESS?

In the present context, crashworthiness is defined as the study of vehicle survivability under the impact with another object. It is the focus on survivability which differentiates a crashworthiness analysis from other kinds of vehicle dynamic analysis. Crashworthiness analyses include the simulation of multi-car collisions, impacts of automobiles into highway barriers, as well as aircraft collisions with terrain or airborne objects such as birds.

The Laboratory's involvement with crashworthiness began in a passive role in the mid 1980's, when many carmakers began using our DYNA3D software for crashworthiness analysis and providing us feedback on its performance. Recently, the Laboratory has taken a more active role in crashworthiness analysis through a DOT highway project, the DOE Auto Initiative, and involvement in the Electric Vehicle Consortium.

Crashworthiness is the study of vehicle survivability under impact with another object.

- Auto/Auto
- Auto/Highway barrier
- Aircraft/Terrain
- Aircraft/Bird

LLNL's involvement in crashworthiness began with DYNA3D, and more recently:

- DOT Highway Project
- DOE Auto Initiative
- Electric Vehicle Consortium

CHARACTERIZATION OF CRASH EVENTS

Crash events are characterized by highly dynamic transient structural response of 5-100 millisecond duration. Mechanical contact conditions are almost always present. In addition, vehicle crash events frequently involve large deformations of thin structures and highly inelastic material response. These characteristics suggest explicit nonlinear finite element analysis as an effective tool for crashworthiness analysis.

Crash events usually involve:

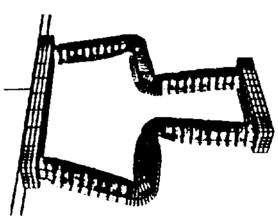
- Transient dynamic effects (5-100 ms duration)
- Mechanical contact conditions
- Large deformations of thin structures
- Inelastic material response

These characteristics often motivate the use of an explicit nonlinear finite element code for crashworthiness analysis.

CRASH STUDIES USE FINITE ELEMENT MODELS AT SEVERAL LEVELS

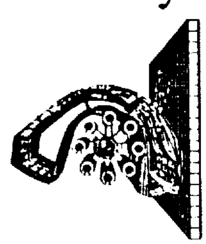
Although many people identify crashworthiness analysis with very large full-body models, effective crash analysis is often conducted with a hierarchy of models. These models range from single components to subassemblies containing a small number of components to full vehicle models. The appropriate level of model complexity is selected based on considerations of simulation accuracy versus the time required to construct the model, run the analysis, and interpret the results.

Component



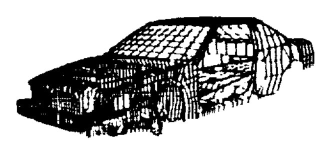
rail collapse

Subassembly



B1-B side impact

Full Vehicle



frontal impact

Tradeoff is simulation accuracy vs. time to:

- Construct model
- Run analysis
- Evaluate results

KEY DYNA3D CAPABILITIES FOR CRASHWORTHINESS MODELING

The following viewgraphs discuss some of the capabilities of DYNA3D which have been found important for crashworthiness modeling. The selection of these features as key capabilities was based on both our experience at LLNL and on extensive feedback received from the DYNA3D outside user community. Viewed collectively, this list of capabilities depicts a general computational simulation capability which is representative of the current state-of-the-art in crashworthiness software used for production analysis, including both DYNA3D and its derivatives as well as other explicit FE crash codes.

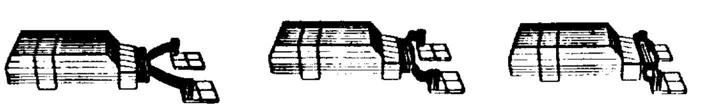
Based on our experience + feedback from user community:

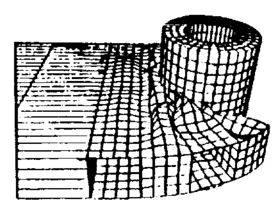
- Rigid materials/bodies
- Good structural elements (shells and beams)
- Fast unilateral contact
- Robust general contact algorithms
- Variety of constitutive models
- Failure modeling

KEY CAPABILITIES - RIGID MATERIALS/BODIES

The capability of modeling portions of a vehicle as rigid and other portions as deformable in the same analysis is quite useful in crashworthiness analysis. So-called "rigid materials" can be used to correctly represent the mass and inertial properties of part of a vehicle which experiences little deformation at a small fraction of the cost required if all deformable materials were used. Another common application of rigid materials is the inexpensive definition of a complex curved surface for contact calculations, such as a rigid pole or partial barrier to be struck by an oncoming vehicle. Finally, rigid materials serve as a powerful model debugging feature. Portions of the model can be easily changed from deformable to rigid, thereby isolating regions of the model which may be the source of difficulties.

- Define all elements of a specified material as composing a rigid body (inertial properties automatically computed from geometry or specified by analyst)
- Greatly reduces cost compared to deformable elements
- Useful for:
  - representing mass properties for parts of vehicle experiencing little deformation
  - defining a complex rigid surface for contact
  - model debugging



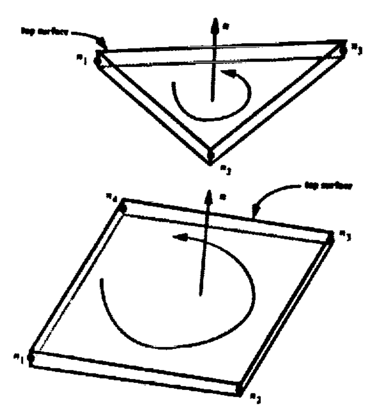


KEY CAPABILITIES - GOOD STRUCTURAL ELEMENTS

A variety of good structural elements are essential for vehicle crashworthiness analysis. DYNA3D contains a library of quadrilateral and triangular shell elements, each with unique capabilities. All elements share the common features of one-point in-plane integration with stabilization of zero-energy modes, and variable order numerical integration in the through-thickness direction.

A family of shell elements with common features gives versatility.

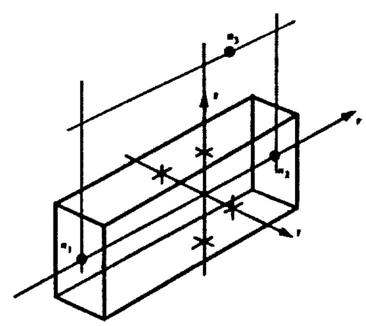
- One point in-plane integration with stabilization
- Variable-order numerical integration thru-thickness
- Shell elements (4-node quads and 3-node triangles):
  - Hughes-Liu
  - Belytschko-Tsay
  - C^o triangle
  - BCIZ triangle
  - Membrane (derived from B-T)
  - YASE



Most large crashworthiness models use some beam elements to represent vehicle structural members. DYNA3D contains the Hughes-Liu beam element and the Belytschko-Schwer beam element. The Hughes-Liu beam uses numerical integration in the cross section and contains a moveable reference surface, and is therefore more general but also more expensive. More commonly used in crash problems is the resultant-based Belytschko-Schwer beam element.

Beams are also frequently useful in vehicle modeling.

- Beam elements:
  - Hughes-Liu
  - Belytschko-Schwer
  - Simple truss

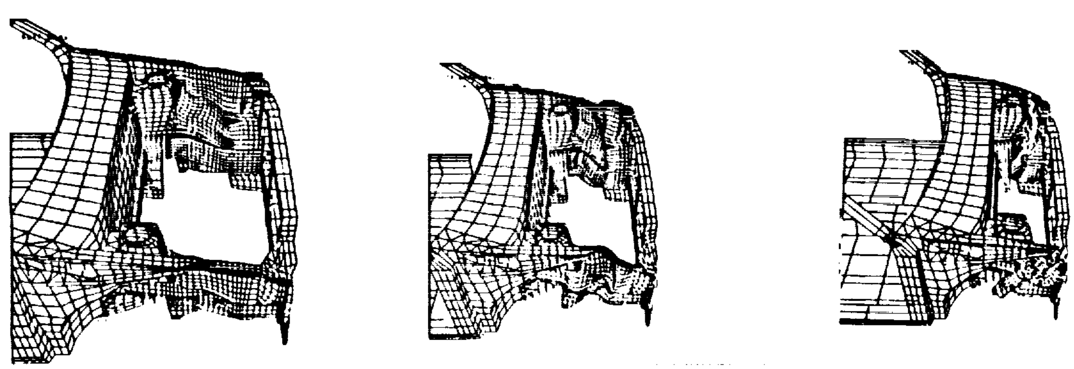


- One point integration along the length
- Hughes-Liu uses variable-order numerical integration in the cross-section for accurate nonlinear material behavior
- Belytschko-Schwer is simple resultant formulation (much less expensive)

KEY CAPABILITIES - UNILATERAL CONTACT (RIGID WALLS)

Unilateral contact, known as "rigid walls" in DYNA3D, is another widely used feature for crashworthiness analysis. This option allows a simple definition of a rigid plane for contact, and is often used to simulate vehicle barrier crash tests. Unilateral contact offers execution speed and modeling simplicity as advantages over discretizing the barrier and using general two-surface contact to treat the impact conditions.

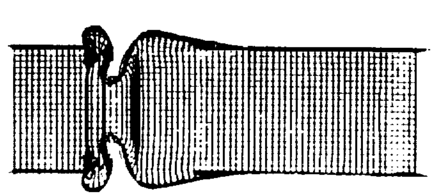
- Applicable for deformable vehicle impact onto rigid barrier
- Much less expensive than discretizing target and using general contact formulation
- Often used for auto frontal crash

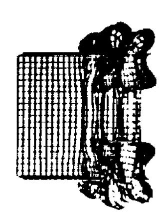


KEY CAPABILITIES - ROBUST GENERAL CONTACT

Robust general contact algorithms may be the most important capability in a crashworthiness code. DYNA3D contact is based on a slave node on master segment concept, and a two-way symmetric treatment is used to eliminate any bias in the calculations. Important components of this capability are the treatment of contact between solid and shell elements, between beams and other element types, and single surface (self) contact.

- Slave node on master segment, symmetric treatment, penalty-method based
- Two-surface algorithm:
  - arbitrary interaction of rigid and deformable bodies
  - general treatment of solids and shells, beams by node only
  - incremental search
- Single-surface algorithm (self-contact) - buckling and folding





KEY CAPABILITIES - FAILURE MODELING

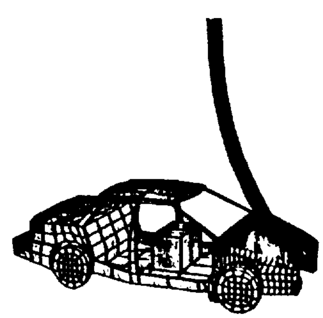
Failure modeling is evolving as a useful tool for crashworthiness modeling. Current approaches in DYNA3D include nodal constraint release options, material-based failure, and element deletion based on a failure criterion. Although these approaches have repeatedly proved their value to skilled analysts, they are somewhat ad-hoc and lack theoretical basis in general settings.

- Nodal constraint release
    - "tie-breaking shell slidelines"
    - "tied node sets with failure"
- Material-based failure - element no longer carries stress (deviatoric or total)
- These approaches are somewhat ad-hoc and may be mesh-dependent, but have proven useful to skilled analysts
- Significant improvements are needed here.

CRASHWORTHINESS SIMULATION ACTIVITIES AT LLNL

Crashworthiness efforts at LLNL include both computational methods research and applications.

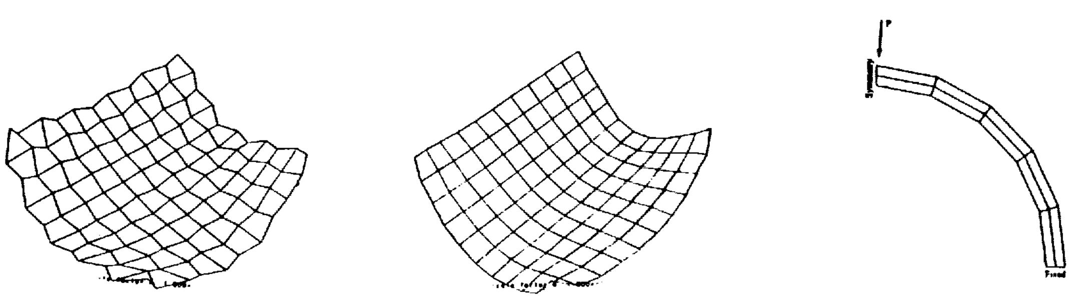
- Computational methods
  - YASE shell - resistant to hourglassing
  - SAND - adaptive slidesurfaces for failure modeling
  - Constitutive models and failure criteria - metals and composites
  - ParaDyn - massively parallel DYNA3D
- Simulation techniques



YASE SHELL ELEMENT

The YASE shell element is a recent outgrowth of research at LLNL. This element is a four-node quadrilateral which extends ideas and the coordinate system of the Belytschko-Tsay element. In the YASE shell, the stabilization evolves directly from the formulation and there are no free parameters which must be chosen by the user. This element yields improvements in accuracy over the Belytschko-Tsay element, and is comparable in performance to more recent elements developed by Belytschko and coworkers. The YASE shell as implemented in DYNA3D is within 10% of the speed of the Belytschko-Tsay element and therefore does not represent a substantial increase in analysis cost.

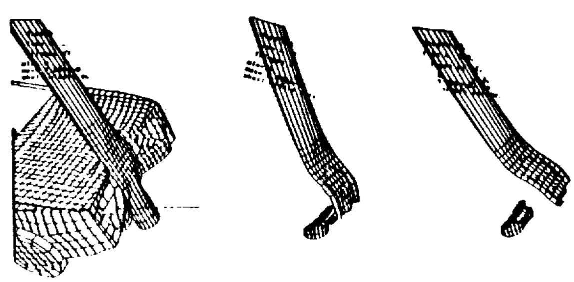
- Builds on ideas and coordinate system of Belytschko-Tsay
- Four-node quad, resultant-based, element normal
- Stabilization evolves directly from the formulation - no "tunable parameters"
- Good coarse mesh accuracy, especially for in-plane bending
- Speed competitive with Belytschko-Tsay (the fastest DYNA3D quad shell)



SAND-SLIDESURFACES WITH ADAPTIVE NEW DEFINITIONS

A recently developed DYNA3D capability for modeling material failure on contact surfaces is SAND (Slidesurfaces with Adaptive New Definitions). Engineering analysts have found SAND useful in modeling bird impacts on windshields and airframes as well as vehicle impacts on soft "frangible" roadside structures. SAND acts as an algorithmic vehicle to implement failure in an explicit finite element code; the difficult task of defining appropriate failure criteria for different problem classes remains a significant area of research.

- Models material failure on contact surfaces
- Failed elements are deleted and contact surface adapts to new outer material boundary
- Permits structural modeling using solid and shell elements
- Allows penetration and failure modeling in Lagrangian framework
- Useful for bird strikes on airframe, vehicle impacts on multiple soft barriers



PARADYN - MASSIVELY PARALLEL DYNA3D

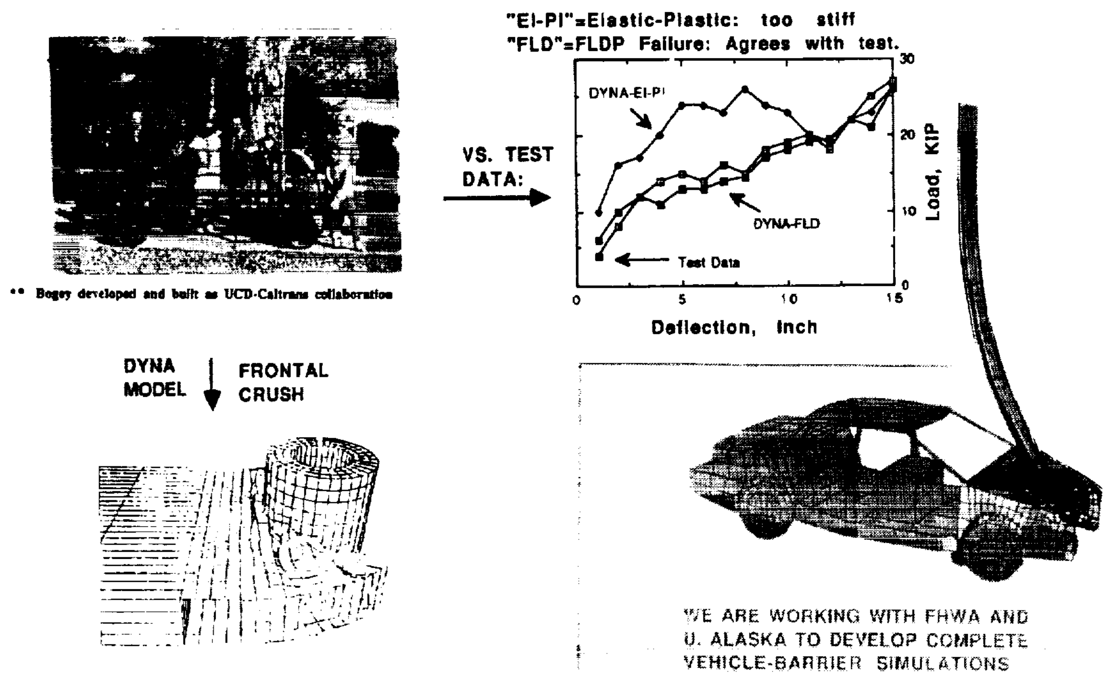
The development of massively parallel explicit nonlinear finite element software is the goal of the LLNL ParaDyn Project. The move to massively parallel computing hardware will allow the solution of much larger problems with reduced turnaround times. It is important to realize, however, that MPP may not offer large speedups for today's small and moderate-sized problems due to difficulties with load balancing and multiprocessor overhead. The true potential of MPP-based analysis lies in the ability to incorporate levels of modeling detail which are totally infeasible with current computing hardware, and in the promise of improved price/performance across a range of machines.

Major Objectives:

- Develop a new generation of DYNA codes to take full advantage of teraflop computing platforms
- Solve significantly larger problems in times commensurate with design cycles
- Determine the architecture and parallel programming models best suited to explicit finite element methods
- Architectures: CM-5, KSR, Intel, Cray MPP0
- Programming Models: F90, HPF, Message Passing
- Establish a community of university and industrial collaborators

DYNA3D IS USED TO MODEL THE UCD/CALTRANS TEST BOGEY. PROPER MATERIAL MODEL IS NEEDED FOR AGREEMENT WITH TEST DATA

One recent LLNL crashworthiness study involved modeling a frontal crush unit tested on the UC Davis/Caltrans test bogey. The graph shows that agreement between the force-displacement curves measured in the experiment and predicted by DYNA3D was significantly improved when the forming-limit failure criterion was added into the DYNA3D model. Other LLNL crash activities include modeling the impact of the vehicles into various roadside barriers and objects such as light poles.



DATA WAS SUPPLIED BY NHTSA FOR A 30 MPH FRONTAL IMPACT. THAT EVENING, WE RAN OUR SATURN MODEL "AS-IS" IN POST-PREDICTIVE MODE

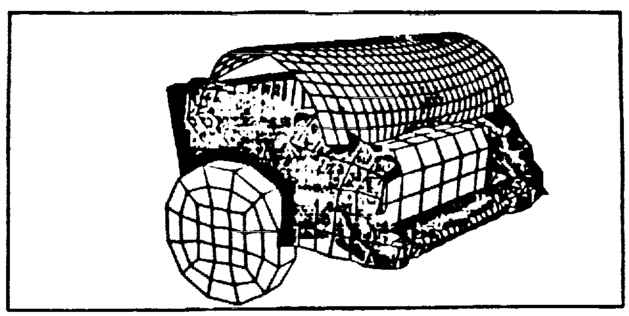
Another recent crashworthiness effort at LLNL consisted of taking our simplified Saturn model (developed in collaboration with J. Wekezer and shown on the lower right of this figure) and simulating a 30 mph frontal crash into a rigid barrier. Test data was supplied by the National Highway Traffic Safety Administration (NHTSA) at three locations: front brake caliper, engine, and rear seat. This was not intended as a detailed modeling effort, but rather an appraisal of the usefulness of our highly simplified car model for representing gross response behavior in an auto crash scenario.

Accelerations were supplied by NHTSA

At three locations:

- **Wheel**
- **Engine**
- **Rear Seat**

These were compared to the first and only DYNA3D run



DYNA3D ACCELERATIONS OF ENGINE AND REAR SEAT AGREE WITH TEST DATA, ALLOWING FOR BUMPER CRUSH

The simplified Saturn model was run once in DYNA3D for the 30 mph frontal crash, and the results were compared with test data for the engine block and rear seat locations. Reasonably good agreement was obtained considering that the model pre-dated the test data and was not tuned, and considering that the model was of a size and complexity to permit overnight analysis on an engineering workstation. Although clearly not a replacement for detailed full-body crashdynamics models, this does illustrate that useful results can be obtained with carefully defined simple finite element models.

At Engine Block:

- **DYNA curve affect 30ms for bumper crush**
- **DYNA shows less rebound due to rigid motor mounts**

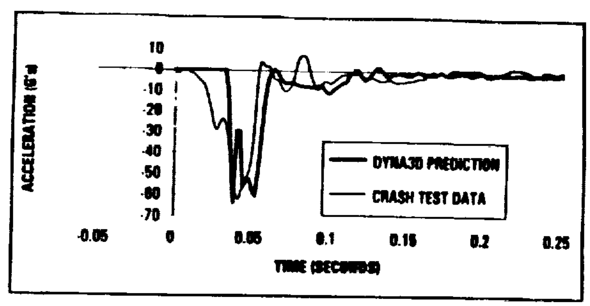
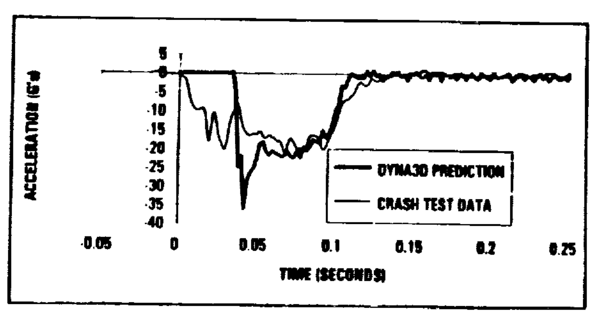


Fig. 10. Acceleration history of the engine block.

At Rear Seat:

- **DYNA shows early peak due to rigid model aft of firewall**
- **Overall impulse and duration agrees, allowing for bumper crush**



FUTURE DIRECTIONS

Although substantial progress has been made in the computational modeling of vehicle crashworthiness in recent years, clearly much remains to be done. The computational modeling of composite materials, particularly under severe dynamic axial loads, remains an area in need of additional research. The general area of failure modeling, including both metals and composites, needs a more fundamental basis and more robust computational methods. The treatment of small scale structural details such as fasteners and spotwelds in a large crashworthiness model merits examination. As in the case of failure models, ad-hoc methods exist which usually work in the hands of skilled analysts, but lack theoretical foundation and are difficult to apply in new situations without substantial reliance on small-scale experiments.

In conclusion, there is an opportunity for shared benchmark problems to be posed as a vehicle for communication among the research, code development, and engineering analysis communities in both the automotive and aerospace industries. These benchmarks could serve as illustrations of current needs in industry and as concrete objectives for researchers and code developers. These should be viewed as learning exercises and growth opportunities by all parties, however, and should not be viewed as software evaluation criteria.

- Improved constitutive models for composite structural failure, especially axial compression - need increasing with growing use of composites in aircraft and vehicles

- Improved progressive failure modeling - current procedures are ad-hoc but usually work. Need better basis and more robust methods

- Special elements for modeling spotwelds and other small-scale features. Current tied-node capability (DYNA3D) is not sufficiently general and may excite hourglassing.

- There is a strong need in both aerospace and automotive areas for shared benchmark problems of current relevance. These could be a strong vehicle for communication between crashworthiness analysis and research communities.